

INSTRUMENTS AND METHODS OF INVESTIGATION

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Lasers and fiber optics for astrophysics

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Contents

Abstract. **Optical spectroscopy has been and remains an important feature of astrophysical research. Huge telescopes are being built to collect radiation from the most distant stars in the Universe for subsequent study with unique astronomical spectrographs. The fundamental problem to be faced here is that of transferring the extremely weak radiation focused by a moving telescope to the entrance of a stationary spectrograph. The solution is to connect a telescope to a spectrograph through an optical fiber, and research and development of the system's necessary components is currently a major task in the field of fiber optics. A key problem in astronomical spectroscopy is the precision measurement of Doppler line shifts in the spectra of stars to determine the velocity of a star movement along the observation line (ray velocity, RV). A remarkable feature of Doppler spectroscopy is that a precision measurement of quite small RV variations (in fact, accelerations) can last for long periods of time. Such star RV variations can be due, for example, to a planet orbiting the star; the action of the planet causes periodical changes in the motion of the star, thus leading to a Doppler shift of the star's spectrum. The precise measurement of this shift has provided an indirect method for searching for and discovering planets outside the Solar System (exoplanets). The important particular problem of searching for habitable earthlike exoplanets requires a spectral measurement accuracy sufficient to detect RV variations at the level of a few centimeters per second per year. Ten to fifteen years of such measurements would provide a direct estimate of the hypothetical accelerated expansion of the Universe. However, the accuracy required for this is more than conventional spectroscopy techniques (iodine cell and spectral lamps) are capable of. This paper reviews approaches to radically improving Doppler spectroscopy techniques to achieve the required shift measurement accuracy. These approaches include the development of fiber-optic systems for connecting the telescope with the astronomical spectrograph and the development of precision calibrators of astronomical spectrographs based on the advances in laser physics and fiber optics.**

Keywords: fiber-fed astronomical spectrographs, Doppler spectroscopy, optical frequency comb, exoplanets, dynamics of the Universe

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1. Introduction

Astronomy, which has gradually developed into astrophysics, is an ancient exact science closely related to mathematics and physics. Discoveries in astronomy exerted a huge influence on our knowledge of Nature. At the same time, space objects were always objects of religious worship. In our time, astronomical knowledge is also accompanied by pseudoscientific — and, in fact, false scientific — considerations based on ignorance. Thus, 'profound' reasonings can often be encountered about Ufology, aliens flying over the whole Universe like a flock of sparrows and even leaving traces on Earth. Plans for interstellar ships with thermonuclear engines or a 'stellar sailboat' accelerated by laser radiation up to velocities close to the speed of light are discussed. All this is based on the conscious or unconscious disregarding of the two facts reliably established by science: the finite speed of light, and huge cosmic distances measured in light years, i.e., the distance that light travels in a vacuum in one year. Therefore, two-way communication with possible habitable exoplanets and, all the more, the launching of research probes are out of the question. The real method for studying space objects is based on the collection and analysis of radiation emitted by them. These investigations involve huge cosmic distances and correspondingly long propagation times over them, even at the speed of light. The longer the distance from the object under study, the more remote in time the phenomenon investigated in it. In this respect, astrophysics is similar to paleontology and archeology.

An efficient method of astrophysical studies is optical astronomic spectroscopy. For this purpose, light from stars located at huge distances is collected with a telescope and directed into a spectrograph. The aspiration to study objects at distances up to billions of light years resulted in the construction of giant telescopes. A telescope mirror up to a few dozen meters in diameter is required to provide the intensity of collected and focused radiation sufficient for studying its spectrum. Extremely low-intensity light focused in the telescope is directed to the entrance aperture of an astronomical spectrograph, which must have the required spectral resolving power and high sensitivity. This requires the use of large echelle type diffraction gratings and a highly mechanically and temperature stable optical design.

Astronomical spectrographs are stationary setups a few dozen meters in size with extremely high mechanical and temperature stability. These unique systems have their own names — acronyms such as HARPS (High Accuracy Radial velocity Planet Searcher), the spectrograph for exoplanet searches based on precise RV measurements; ESPRESSO (Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observation), the spectrograph for searching for solid Earth-like exoplanets and stable spectral observations, and CODEX (COsmical Dynamics EXperiment), the spectrograph for direct investigations of the dynamics of the Universe. A fundamental problem appears of sending radiation collected by a moving telescope to the entrance aperture of an immobile spectrograph without losses or distortions. This problem is solved by developing a special fiber-optic communication line.

One of the problems with astronomical spectroscopy is the precise measurement of the Doppler shift of the spectrum of a star. Such measurements allow the ray velocity (RV) of the star to be determined. Measurements performed at different time intervals give the time variation of the RV, i.e., the acceleration of the star movement. This is the Doppler astronomical spectroscopy. An outstanding achievement was the discovery of the redshift of the spectrum of distant galaxies proportional to the distance to them (Hubble's law), on which the concept of the expanding Universe after the Big Bang is based. In this case, Doppler shifts are very large and the corresponding RV variations amount to a few fractions of the speed of light.

However, small Doppler shifts can also give very important results. Thus, precise investigations of Doppler shifts of the spectra of stars for long time intervals showed [1] that the RV of a star under study experienced small but strictly periodic variations, i.e., the star's motion exhibited small periodic accelerations. This was interpreted as the influence of a planet revolving around the star on the star's motion. The star and planet revolve around their common center of masses, resulting in periodic RV variations. These observations were the first to prove indirectly but reliably the existence of planets revolving around stars beyond the Solar System (exoplanets).

The Doppler spectral shift and the corresponding RV change depend on the star/planet mass ratio. For example, the revolution of Jupiter around the Sun causes variations in the Sun's motion which would show for an external observer a maximum RV change of 12 m s^{-1} with a period of 12 years, whereas Earth's revolution would cause only a 9-cm-s^{-1} RV change with a period of 1 year. This means that, to discover Earth-like exoplanets revolving around Sun-like stars, the measurements of the spectral Doppler shift should be accurate to the 10th decimal place. Because such measurements involve comparisons of spectra recorded at different times, the precise calibration of a spectrograph is required, which is performed by recording, together with the spectrum under study, the spectrum of a source with well-defined spectral lines, for example, spectral lamps or iodine absorbing cells. The calibration accuracy is characterized by the minimal RV difference that can be determined during prolonged measurements. For spectral lamps and iodine cells, the calibration accuracy is no less than a few meters per second, which allows the discovery of Jupiter-like planets, but not Earth-like ones. To discover and study Earth-like planets, a spectrograph calibrator with an accuracy of a few centimeters per second is required. Such calibrators are designed on the base of lasers.

2. Fiber-optic telescope–spectrograph coupling

A modern astronomical spectrograph is always coupled with a telescope through an optical fiber (fiber-fed spectrograph). Unlike widely used fiber-optic communication lines employing single-mode optical fibers (SMFs) operating in a rather narrow spectral band, the fiber-optic telescope–spectrograph coupling should provide the transfer of extremely weak radiation without spectral distortions in a broad spectral range to the entrance slit of a spectrograph. The optical fiber not only transfers light from a telescope to a spectrograph but also provides the illumination of the entrance slit of the spectrograph required to obtain the best resolution and high stability of spectral measurements, because the maximum resolving power of the spectrograph depends on the slit illumination. In fact, it is not a common fiber-optic communication waveguide that is required, but a light guide for illuminating the entrance slit of the spectrograph. For this purpose, specially developed systems based on multimode optical fibers (MOFs) with large core diameters (up to a few hundred micrometers) are used.

Because images in a telescope's focus are micron-sized, a system of microlenses is required for matching the fiber aperture with the entrance slit of the spectrograph. Upon propagation of radiation in an optical fiber with a large core diameter, a great number of modes are excited in the fiber, their propagation being dependent on the core size, fiber bend, mechanical stresses, etc. An important feature of an optical fiber is its ability to scramble the many radiation modes propagating in it. This scrambling plays a significant role in the operation of a fiber-fed spectrograph. A micron-sized star image is projected by a microlens on the input end of an optical fiber up to hundreds of microns in diameter. Because of a number of external conditions, for example, some inaccuracy in the telescope's motion (guiding), the star image moves somewhat over the fiber end cross section. This is transferred to the radiation distribution at the fiber output and, finally, at the spectrograph detector. The weaker the dependence of radiation distribution displacement at the detector on the star image displacement at the fiber input, the higher the accuracy of spectral measurements.

It was shown in Ref. [2] that the mode scrambling degree strongly affects the operation of the fiber-optic coupling of an astronomical spectrograph. The scrambling gain is defined as the ratio of the relative change in the radiation intensity distribution at the fiber input to that at the fiber output. Its value depends on the communication line design, and it is important to increase this gain. Because Doppler spectroscopy is based on a comparison of spectra obtained at different times, the mode scrambling also depending on fiber bends should be invariable and maximal. For this purpose, fibers are subjected to special mechanical action, being periodically bent at frequencies of tens of hertz.

To study the mode scrambling process in MOFs, a method was proposed in Refs [3, 4] involving the simultaneous measurement of the spatial radiation distribution in the far and near zones at the fiber output. Radiation from a broadband source (a set of optical diodes) is formed by a lens system into a beam directed onto the fiber under study. The radiation intensity distribution over the fiber output cross section is measured with a microscope objective displaced by a precise translator. This method was applied to study MOFs with core diameters of about 200 μm and different core shapes: square, hexagonal, octagonal, and circular [3, 4]. The mode scrambling gain proved to be strongly determined by the properties of the fiber core–shell interface. Fibers with octagonal cores were the best for required applications.

New types of MOFs that have appeared recently have large-diameter hollow cores [5, 6]. Their advantage is the absence of absorption losses. Because the core–shell interface in these fibers fundamentally differs from that in common MOFs and the mode filling and scrambling depend on it, it is important to study the possibility of using such fibers in fiber-fed astronomical spectrographs. These studies require fibers whose production is completely determined by modern science-intensive technology. Advances in the technology for manufacturing optical fibers resulted in the development of a special area in the production of fiber-optic coupling systems for astronomical spectrographs based on a combination of single-mode and multimode fibers. Single-mode fibers with small-diameter cores are used, which are assembled into a bunch, producing a large-diameter optical fiber consisting of many SMF cores, i.e., a multicore fiber (MCF) [7].

Figure 1 shows the design of such a fiber. It consists of 120 single-mode cores in which Bragg gratings can be written by a femtosecond laser. The gratings are used for filtering the spectrum of transferred radiation to eliminate the undesired spectral lines in order to improve the detection of the spectrum under study. The MCF ends are coupled through couplers and MOF segments with a telescope and a spectrograph.

The further development of the production technology of optical fibers resulted in the MCF improvement [8]. Figure 2 displays the cross section of an MCF consisting of 511 individual single-mode cores. The study of this fiber showed that it surpasses MOFs with an octagonal core. Combinations of MOFs with MCFs are considered a promising approach to improving the astronomical fiber-optic telescope–spectrograph coupling [9].

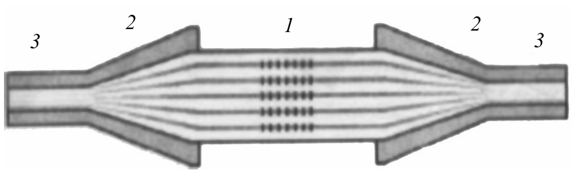

Figure 1. Multicore fiber with Bragg gratings written in each core. The ends of the fiber are connected via couplers with MOF segments: (*1*) single-mode cores with written Bragg gratings, (*2*) couplers, and (*3*) MOF segments.

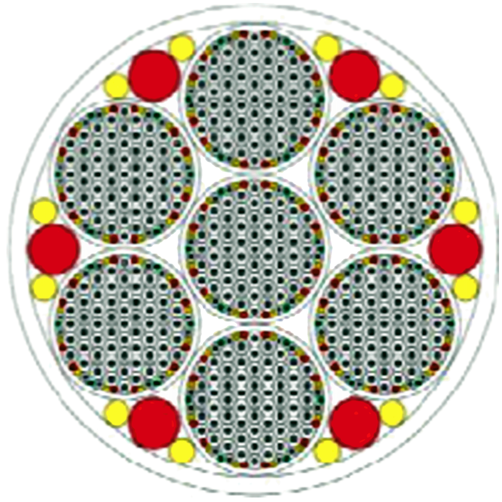

Figure 2. Cross section of an MCF 562 μm in external diameter consisting of 511 single-mode cores with diameters from 1.8 to 3.4 μm separated by distances from 4.8 to 5.8 μm [8].

3. Precision calibration of an astronomical spectrograph

As mentioned above, to measure RV differences with an accuracy at the centimeter-per-second level, the corresponding high-precision calibration of an astronomical spectrograph is required. Spectrometers are usually calibrated by recording the spectral lines from a reference light source with precisely known wavelengths (frequencies). For astronomical spectrographs, they are hollow cathode type spectral lamps filled with argon with an admixture of thorium or uranium, as well as cells with iodine vapors having narrow absorption lines of I_2 molecules. For a number of reasons, such a calibration cannot provide in prolonged RV measurements an accuracy better than a few meters per second. However, the important astrophysical problem of searching for a solid Earth-like exoplanet revolving around a Sun-like star requires an accuracy of a few centimeters per second in stable measurements performed for more than a year. Even better accuracy, at the 1-cm-s^{-1} level, is required for spectral measurements aimed at direct studying the expansion dynamics of the Universe for 15–20 years.

Lasers can generate optical radiation with extremely narrow spectral lines at frequencies which can be precisely determined with the help of frequency standards. Thus, narrow spectral lines at precisely defined wavelengths can be synthesized, and we can say figuratively that laser science and technology allow us to create an 'artificial atom' with precisely defined wavelengths of spectral lines. It is well known that a passively mode-locked continuous-wave (cw) laser has the unique feature of generating a continuous strictly periodic train of femtosecond pulses, and its spectrum consists of a comb of extremely narrow, closely-spaced, equidistant spectral lines with an extent corresponding to the pulse duration. The shorter the laser pulses, the broader the comb spectrum. Thus, such a laser is a source of an optical frequency comb (LOFC).

The spacing between the lines of the frequency comb is determined by the femtosecond pulse repetition rate. In due course, the pulse repetition rate is determined by the optical length of the laser resonator, which can be precisely con-

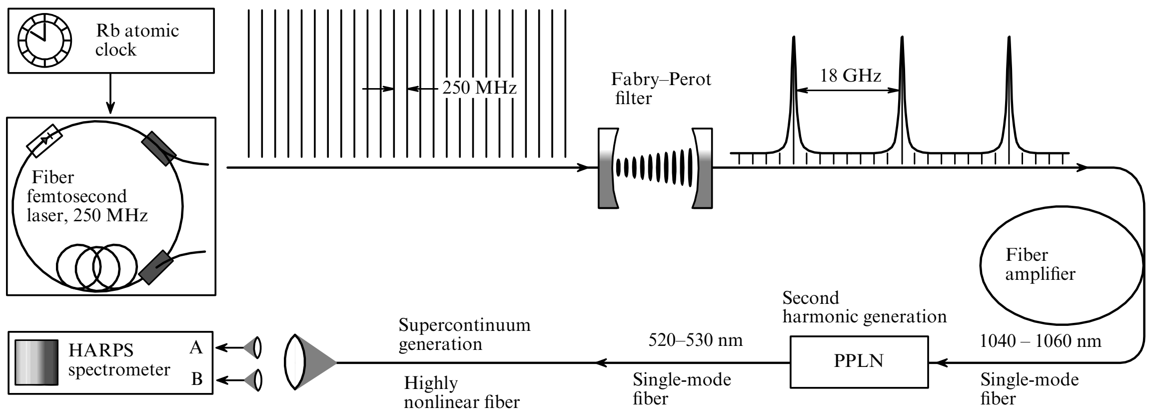

Figure 3. Basic setup of a calibrator for an astronomical spectrometer.

trolled by piezoelectric devices. Thus, we have a source of spectral lines separated by the exactly defined spacing. Because the intensity of femtosecond pulses is high, they can be frequency-converted by nonlinear optics methods, and the LOFC spectrum can span the entire optical range.

A unique feature of LOFCs has led to outstanding advances in precision metrology with an accuracy better than 17 decimal places, including the creation of ultraprecision optical clocks, precision measurements of the Rydberg constant, and the transmission of precision frequency and time signals over distances of hundreds kilometers. Studies in this field were recognized by the Nobel Prize in Physics 2005 [10]. Successful LOFC applications are considered, for example, in papers [11–14]. The method of LOFC measurements is described in detail in Ref. [15].

It is natural to use LOFCs for precision calibration of astronomical spectrographs. However, this involves a significant difficulty. Typical frequency spacings between the 'teeth' of the comb for widely used femtosecond Ti:sapphire lasers do not exceed 1 GHz, whereas for fiber femtosecond lasers the spacing is even smaller ($\sim$ 250 MHz). At the same time, the spectral resolution of even the best astronomical spectrographs are no less than a few GHz. This means that LOFC lines cannot be resolved by such spectrographs and will merge. This drawback can be eliminated by filtering the LOFC spectrum with the aid of Fabry–Perot etalons [16–18].

A Fabry–Perot etalon has narrow transmission bands at resonance frequencies (modes) determined by the spacing between its mirrors (etalon thickness). If the etalon thickness is m times smaller than the optical length of the laser resonator, the LOFC lines will be transmitted through it with m times the resolution. The etalon thickness and the optical length of the resonator can be piezoelectrically controlled. The etalon transmission linewidth is determined by the reflection coefficient of its mirrors, which is limited by technological capabilities. For this reason, the required LOFC filtration degree can be obtained using only a set of two or even three successive etalons. In combination with such a system of Fabry–Perot etalons, femtosecond lasers enable realizing a synthesizer of spectral lines needed for the precision calibration of astronomical spectrographs designed for Doppler spectroscopy. Numerous schemes of femtosecond lasers required for this purpose are considered in review [19]. The setup based on a Ti : sapphire crystal active medium is considered classical. Using filtration with the help of Fabry–Perot etalons, the LOFC with a 16-GHz spacing between the teeth was obtained and applied, in combination with the HARPS spectrograph, in astronomical studies [20].

Fiber femtosecond lasers are more compact and have better operation characteristics than Ti : sapphire lasers. As a result, such lasers are most often used in LOFC systems. The basic setup of such a precision calibrator for astronomical spectrographs developed at the Institute of Quantum Optics (Germany) and Menlo Systems Company (Germany) and successfully tested [21, 22] is shown in Fig. 3. In particular, the accuracy of calibrators coupled with different spectrographs was compared. These tests, performed for 6 years, showed that the difference in the accuracy of calibrators did not exceed 2.5 cm s^{-1}.

Figure 4 plots the LOFC spectrum recorded with the HARPS spectrograph. Despite these advances, it should be noted that, although this system provides a calibration accuracy at the level of a few centimeters per second, it is very complicated compared to conventional systems based around spectral lamps and an iodine cell. This system requires a perfect femtosecond laser with piezoelectrically controlled spacing of the LOFC stabilized by a frequency standard. A special system is required for controling the fixed position of the LOFC on the frequency scale. For this purpose and also for expanding the LOFC spectrum over the entire visible range, a supercontinuum should be efficiently generated with the help of photonic crystal type optical fibers.

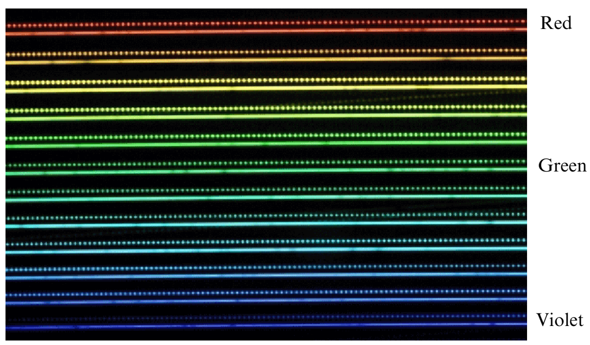

Figure 4. Calibrator comb spectrum recorded with a spectrometer.

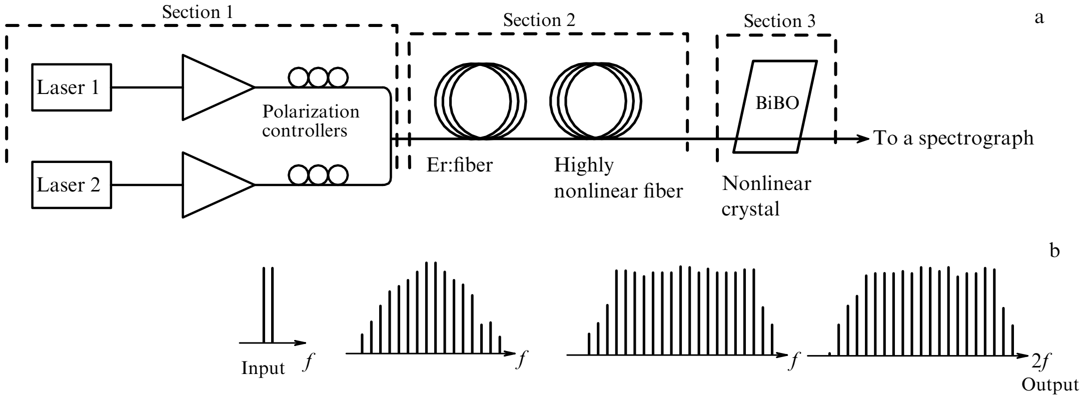

Figure 5. Fiber-optic system for LOFC generation. (a) Basic diagram of the setup, and (b) spectrum conversion in sections of the setup.

Along with the use of cw femtosecond lasers, LOFCs can alternatively be generated by four-wave mixing of intense laser radiation in a nonlinear medium with a certain dispersion. Single-mode optical fibers possess the required properties. Radiation measuring 1.5 μm can be amplified in an Er-doped fiber to the required intensity level, and SMFs widely used in fiber-optic communication systems have anomalous dispersion in this spectral region. Thus, a combination of these fibers can provide the conditions required for realization of the nonlinear effect.

These circumstances have been successfully used to generate ultrashort laser pulses on new principles [23, 24]. Using two cw lasers emitting narrow spectral lines of the same intensity at slightly different wavelengths, we can obtain sinusoidally modulated cw radiation due to beats. The radiation can be amplified and coupled to SMFs possessing nonlinearity and anomalous dispersion. Four-wave mixing causes the sharpening of the maxima of the sinusoid, producing a continuous train of femtosecond pulses.

This effect was used to build a LOFC calibrator for astronomical spectrographs [25]. The basic setup is shown in Fig. 5. The device consists of three sections. In the first, two lasers emitting lines 150 kHz in width in the 1.5-μm region produce a continuous sinusoidal radiation train. The frequency-stabilized radiation from these lasers can produce beats at different frequencies (40, 80, and 160 GHz). In the next section, diode-pumped Er-activated SMFs were used for amplification to obtain the required intensity, as was an SMF-28 with anomalous dispersion. In the third section, this train of femtosecond pulses was converted into the second harmonic and a supercontinuum was generated in a photonic-crystal fiber to obtain a LOFC in the visible range.

Figure 6 illustrates a portion of the LOFC spectrum generated by this method. An attractive feature of this approach is the absence of a femtosecond laser and complicated piezoelectronics. The LOFC spacings can be a few dozen GHz. This means that there is an opportunity to invoke moderate-resolution spectrographs, which is important for expanding the field of exoplanet searches. However, one should bear in mind that it is not simple to increase the LOFC interval, because the latter corresponds to increasing the pulse repetition rate, resulting in an appropriate decrease in the pulse energy and intensity. For this reason, the required nonlinear process may simply not start. In addition, one should take into account various effects limiting the radiation intensity, including the danger of fiber damage. The selection of fiber lengths, pump conditions, etc. require detailed experimental studies.

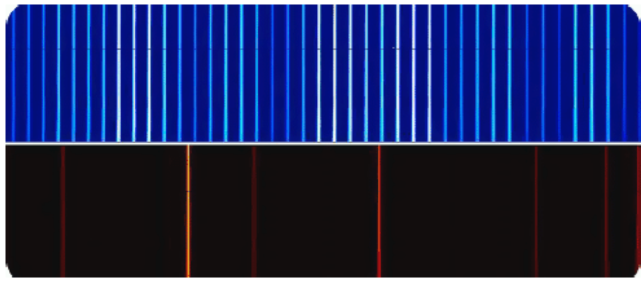

Figure 6. Portion of the fiber-optic LOFC system spectrum (top) and the spectrum of a spectral lamp for comparison (bottom).

Thus, laser physics makes it possible to build sources of narrow spectral lines with exactly defined wavelengths (frequencies) in the optical range. They can be utilized to calibrate astrophysical spectrographs with an accuracy sufficient for measuring Doppler shifts at the level of a few centimeters per second. However, these systems are rather intricate and costly compared to traditional calibrators based on spectral lamps and iodine cells, which, although providing an accuracy only at the level of a few meters per second, are significantly simpler and more efficient in operation than laser systems.

4. Investigations in astrophysics

The method of Doppler astrophysical spectroscopy is making it possible to perform especially important investigations. However, its basic difficulty is that it involves precision measurements of spectra over long time intervals and comparing them. In addition, it should be reliably established that the rather small differences in the spectra that can be observed are caused exclusively by the influence of a star with the corresponding RV. This assumes the absence of any process on the star itself affecting its spectrum. In addition, radiation distortion in the atmosphere should also be taken into account. Distortions during radiation transfer from a telescope through a fiber-optic communication line can also cause errors due to inaccuracies in the telescope guiding. Although the accuracy of calibrators in laboratory studies is on the order of a few centimeters per second, the accuracy of real measurements with astronomical spectrographs is so far an order of magnitude lower.

4.1 Exoplanet research

The main achievement of Doppler astrophysical spectroscopy is the discovery of exoplanets [1]. At present, their number is more than a thousand. These studies are stimulated by the desire to find a habitable exoplanet. It is known that the Solar System contains planets of two types: gas giants like Jupiter and Saturn, and rocky planets like Venus, Earth, and Mars. These planet types differ greatly in size and mass. It was mentioned in Section 2 that the smaller the exoplanet mass, the smaller the Doppler shift, and therefore it is more difficult to discover rocky planets. The necessary condition for the existence of life on an Earth-like planet is the presence of water in the liquid state, i.e., the temperature on the planet's surface should lie in a certain range. This means that the exoplanet should be found at a certain distance from the star in the so-called 'habitable zone'. Thus, the search for solid Earth type exoplanets is limited by the accuracy of RV measurements and by an orbit size.

As mentioned above, the maximum change in the Sun's velocity caused by Earth's orbiting is only 9 cm s^{-1}, which is beyond the accuracy of systematic measurements with modern astronomical spectrographs, while the orbit size corresponds to a period of one year. For stars with smaller masses and lower temperatures, larger Doppler shifts and smaller exoplanet orbit sizes can be expected. Therefore, M type stars (red dwarfs) of smaller sizes attract greater attention of researchers. The small mass of the star reduces the accuracy of Doppler shift measurements to a few meters per second, while the lower temperature assumes the 'habitable zone' orbits with periods at the level of a few dozen days, rather than a year. In addition, stars of this type are the most abundant in the Universe.

Based on these considerations, a large group of researchers from several observatories, astrophysical institutes, and universities carefully analyzed the RV dependences on the observation time obtained with HARPS spectrographs in the study of the Proxima Centauri star. As a result, the Earth-like exoplanet was discovered in 2016, which was called Proxima b [26]. This planet is 20 times closer to its star than Earth is to the Sun, is located in the habitable zone, and makes a full revolution around its star in 11.2 days. Its mass is 1.27 times Earth's mass. The maximum RV change was 2 m s^{-1}, which made possible the application of traditional methods for spectrograph calibration.

To search exoplanets revolving around M type dwarfs, the special CARMENES spectrograph (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs) was built in Calar Alto (Spain) for operation with a telescope 3.5 m in diameter [27]. Because the star temperature is comparatively low, a considerable part of the emitted radiation lies in the near-IR region. CARMENES consists of two separate echelle spectrographs covering the wavelength range from 0.55 to 1.7 μm with resolving power $R = 82{,}000$. Calibration with an accuracy of 1 m s^{-1} is performed using an advanced spectral lamp with a stabilization by the Fabry–Perot etalon. About 300 well-known M dwarfs have been studied. One of the recent results is published in paper [28] (Fig. 7). The importance and urgency of investigations discussed in Ref. [28] is demonstrated by the number of its co-authors (148!) from 28 organizations.

4.2 Time variation of fundamental physical constants

Because the recording of spectra of cosmic objects located at huge distances also means removal in time, it is possible, in principle, to compare a spectrum emitted billions years ago with the spectra of sources existing at present. It is known that Dirac already back in 1937 assumed that measurement scales and fundamental physical constants should change due to the expansion of the Universe. This could cause a change in the fine-structure constant α in time. Precision LOFC measurements make such experiments theoretically possible [29]. For this purpose, the unique ESPRESSO spectrograph intended for operation with the giant VLT telescope was built [30] to study the so-called 'forest' of red-shifted Lyman-α lines and compare them with existing spectra.

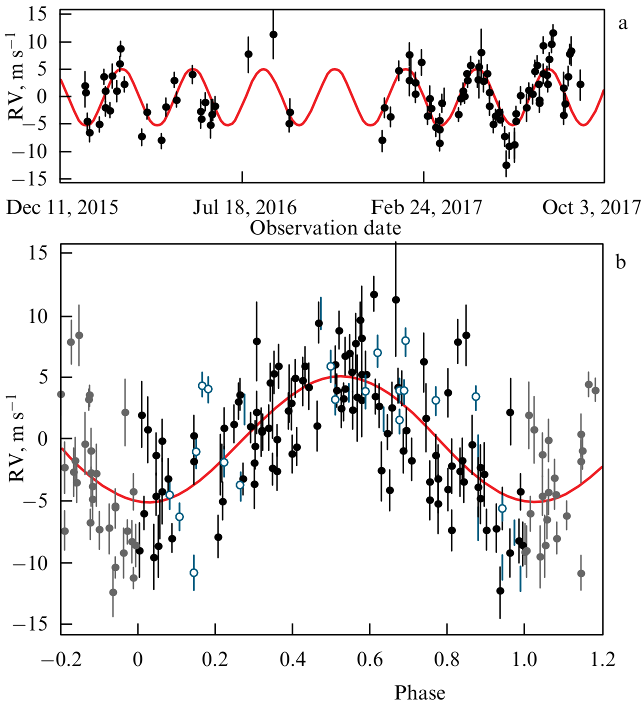

Figure 7. Time variations of the RV (a), the result with the mathematical processing of a great number of data (b) [28].

4.3 Direct measurement of the expansion acceleration of the Universe

Precision spectral measurements of the Doppler shifts of astronomical objects make it possible, in principle, to study in detail the most important problem in modern science: the dynamics of the Universe, namely, to confirm directly the accelerated expansion of the Universe and to investigate the question of dark energy. The idea of such studies was proposed back in 1962 [31]. It was assumed the expansion velocity of certain cosmic objects would be measured accurately from the spectral redshift and then these measurements would be repeated through certain time intervals. The difference in velocities would demonstrate the change in the expansion velocity. However, estimates have shown that, for the accuracy of spectral measurements at that time, hundreds of years would be required to observe a noticeable effect. The use of LOFCs radically changed the situation. To realize this idea, the unique CODEX spectrograph was developed for measuring, in combination with the giant E-ELT telescope, the expansion of the Universe [32]. It is proposed to improve the accuracy of Doppler shift measurement to a few centimeters per second and perform measurements for 15–20 years.

5. Conclusion

Advances in laser physics and fiber optics open up possibilities for important applications in astrophysics, involving precision measurements of Doppler shifts in the spectra of stars. The knowledge-intensive technology of manufacturing optical fibers and the methods of studying them are of great importance. This is extremely important for the operation of unique telescopes in combination with unique spectrographs. A high accuracy of spectral measurements is achieved with the help of LOFCs. Notice that fiber-optic lines for coupling telescopes with spectrographs and precision LOFC calibrators are constantly being updated. To obtain new important results, the cooperation of highly qualified researchers in various fields is required, including astronomers performing investigations on telescopes at observatories, researchers in optics developing and studying spectrographs at astrophysical institutes, technologists in fiber optics developing and studying the required devices, and researchers in laser physics and technology. The high qualification of the researchers is naturally provided by universities. Experience shows that only such a collaboration leads to success. The quest for a solution to the urgent problems of fundamental science strongly stimulates the development of such investigations.

References

1. Mayor M, Queloz D *Nature* **378** 355 (1995)
2. Avila G, Singh P, Albertsen M *Proc. SPIE* **6269** 62695O (2006)
3. Chazelas B et al. *Proc. SPIE* **7739** 773947 (2010)
4. Feder T et al. *Proc. SPIE* **8446** 844692 (2012)
5. Kosolapov A F et al. *Quantum Electron.* **46** 267 (2016); *Kvantovaya Elektron.* **46** 267 (2016)
6. Pryamikov A D et al. *Quantum Electron.* **46** 1129 (2016); *Kvantovaya Elektron.* **46** 1129 (2016)
7. Birks T A et al. *Opt. Express* **20** 13996 (2012)
8. Gris-Sánchez I et al. *Mon. Not. R. Astron. Soc.* **475** 3065 (2018)
9. Leon-Saval S G et al. *Opt. Express* **25** 17530 (2017)
10. Hänsch T W *Rev. Mod. Phys.* **78** 1297 (2006); *Usp. Fiz. Nauk* **176** 1368 (2006)
11. Jones D J et al. *Science* **288** 635 (2000)
12. Holzwarth R et al. *Phys. Rev. Lett.* **85** 2264 (2000)
13. Udem Th, Holzwarth R, Hänsch T W *Nature* **416** 233 (2002)
14. Cundiff S T, Ye J *Rev. Mod. Phys.* **75** 325 (2003)
15. Kryukov P G *Phys. Usp.* **58** 762 (2015); *Usp. Fiz. Nauk* **185** 817 (2015)
16. Steinmetz T et al. *Science* **321** 1335 (2008)
17. Li C-H et al. *Nature* **452** 610 (2008)
18. Steinmetz T et al. *Appl. Phys. B* **96** 251 (2009)
19. McCracken R A, Charsley J M, Reid D T *Opt. Express* **25** 15058 (2017)
20. Glenday A G et al. *Optica* **2** 250 (2015)
21. Wilken T et al. *Nature* **485** 611 (2012)
22. Ycas G G et al. *Opt. Express* **20** 6631 (2012)
23. Dianov E M et al. *Opt. Lett.* **14** 1008 (1989)
24. Mamyshev P V, Chernikov S V, Dianov E M *IEEE J. Quantum Electron.* **27** 2347 (1991)
25. Zajnulina M et al. *Appl. Phys. B* **120** 171 (2015)
26. Anglada-Escudé G et al. *Nature* **536** 437 (2016)
27. Quirrenbach A et al. *Proc. SPIE* **9147** 91471F (2014)
28. Reiners A et al. *Astron. Astrophys.* **609** L5 (2018)
29. Amendola L et al. *Phys. Rev. D* **86** 063515 (2012)
30. Pepe F A et al. *Proc. SPIE* **7735** 77350F (2010)
31. Sandage A *Astrophys. J.* **136** 319 (1962)
32. Pasquini L et al. *Proc. SPIE* **7735** 77352F (2010)